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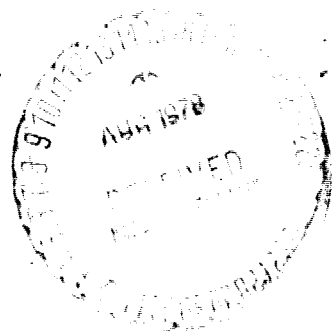
40 KW OF SOLAR CELL MODULES
FOR THE LARGE SCALE PRODUCTION TASK
A LOW COST SILICON SOLAR ARRAY PROJECT

FINAL TECHNICAL REPORT

Gregory T. Jones

December 1977

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This work was performed for the Jet Propulsion Laboratory California Institute of Technology, under NASA Contract NAS7-100, Task Order No. RD-152, for the U.S. Department of Energy Division of Solar Energy.

The JPL Low-Cost Silicon Solar Array Project is funded by DOE and forms part of the DOE Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

(NASA-CR-157348) THE 40 kW OF SOLAR CELL
MODULES FOR THE LARGE SCALE PRODUCTION TASK
A LOW COST SILICON SOLAR ARRAY PROJECT
Final Technical Report (Sensor Technology,
Inc.) 38 p HC A03/MF A01

N78-28602

Unclas
CSCL 10A G3/44 25948

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ABSTRACT

Forty kilowatts of solar cell modules was produced in this program. This is equivalent to 4123 modules. The average power output per module was 9.7 watts at 16.5 volts, 60°C and 100 mW/cm². The peak production rate was 200 modules per week which is equal to 1.9 KW per week. This rate was sustained for over four and one-half months and is equivalent to 100 KW per year.

This final report covers the solar cell module design, electrical and power performance, module preproduction environmental test results, production and shipping schedule, program summary, and delivery. A cost analysis section is written. Particular emphasis on the percentage of labor and material utilized in constructing a solar cell module is presented. Also included are cost reduction recommendations.

It was concluded from this program that volume production on the order of hundreds of kilowatts per year per company as a minimum is required to significantly reduce the price per watt for solar cell modules. Sensor Technology more than doubled its solar cell module manufacturing facilities since the completion of the JPL Block II procurement. Plans are being made for large scale expansion of our facilities to meet growing JPL/DOE procurements.

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INTRODUCTION

The 40 KW of solar cell modules produced by Sensor Technology in this program is part of the JPL Large Scale Production Task, a Low-Cost Silicon Solar Array Project, part of the overall DOE (formerly ERDA) Solar Photovoltaic Program.

The overall objective of the Solar Photovoltaic Program ¹ is to develop low-cost reliable photovoltaic systems and to stimulate the creation of a viable commercial industry to produce and distribute systems for widespread use in residential, industrial and commercial applications.

The Low-Cost Silicon Solar Array Project objectives ² are listed as follows:

- 1) reduce costs of photovoltaic solar arrays
- 2) develop solar photovoltaic technologies for commercial practice
- 3) foster expansion of industry for photovoltaic production
- 4) support market growth
- 5) develop solar arrays with low price (less than \$500/KW), large scale production (greater than 500 MW/year), long lifetime (greater than 20 years), and high conversion efficiency (greater than 10%).

The Large Scale Production Task has as its primary objective ² the supply of silicon solar array modules to DOE's (ERDA's) Photovoltaic Program Demonstration and System Test and Analysis Projects. The purpose of this task is to procure solar cell modules in volume to stimulate the market and assist industry in developing better modules at lower cost.

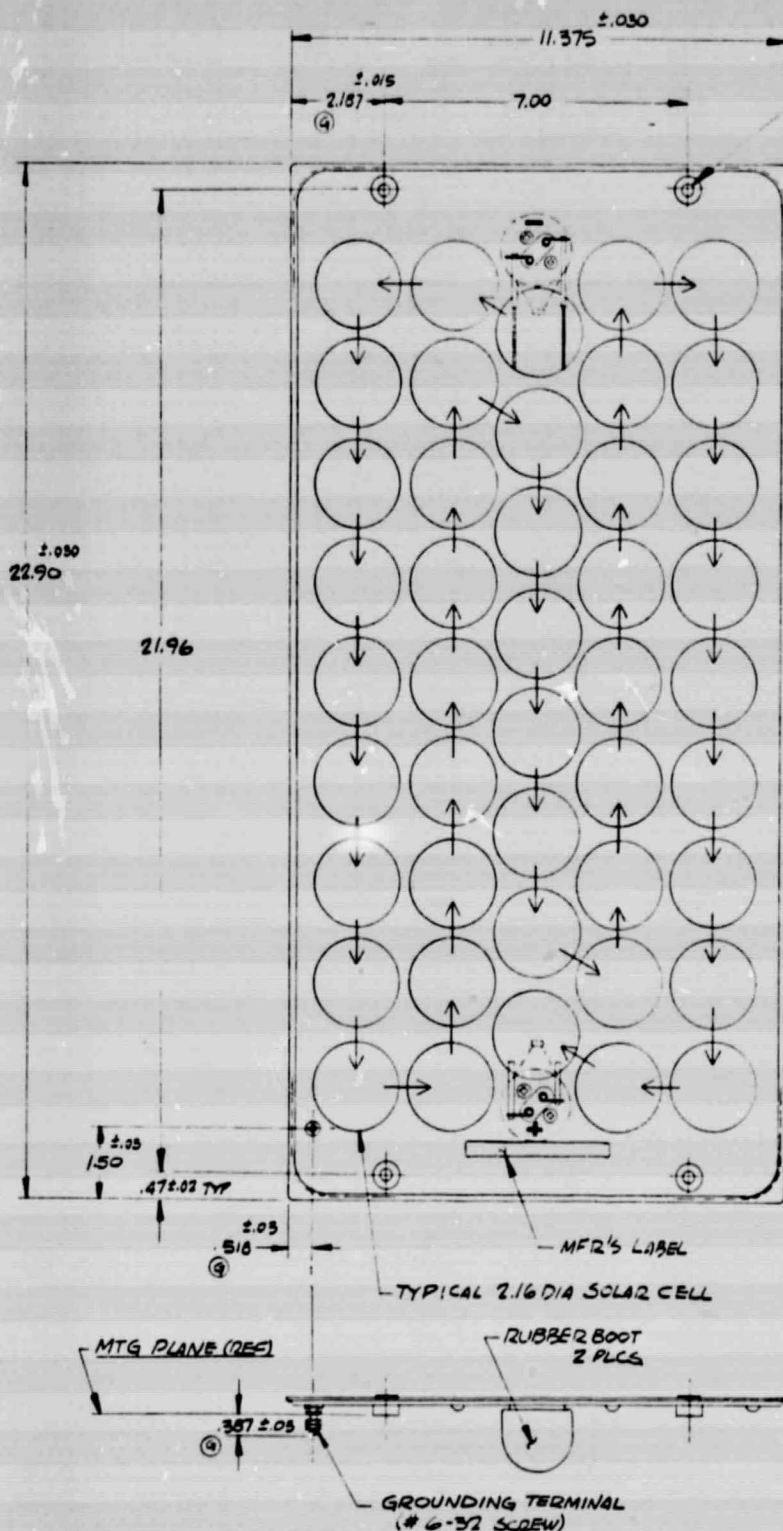
Sensor Technology is one of the principle solar cell module manufacturers in the Large Scale Production Task. Forty kilowatts of solar cell modules was produced in this program. They were utilized in demonstration and system test and analysis projects such as the MIT/Lincoln Laboratory agricultural irrigation project in Mead, Nebraska (25 KW installation); the ERDA/JPL audio-visual equipment demonstration (2KW) for a space symposium at the California Museum of Science and Industry in Los Angeles; and environmental tests, accelerated tests, and data analysis by the Jet Propulsion Laboratory in Pasadena.

This report presents Sensor Technology's final results for the 40 KW procurement program. It covers the solar cell module design, electrical and power performance, module preproduction environmental test results, production and shipping schedule, program summary and delivery. A section on cost analysis is written. Particular emphasis on the percentage of labor and material utilized in constructing a solar cell module is presented. Also included are cost reduction recommendations.

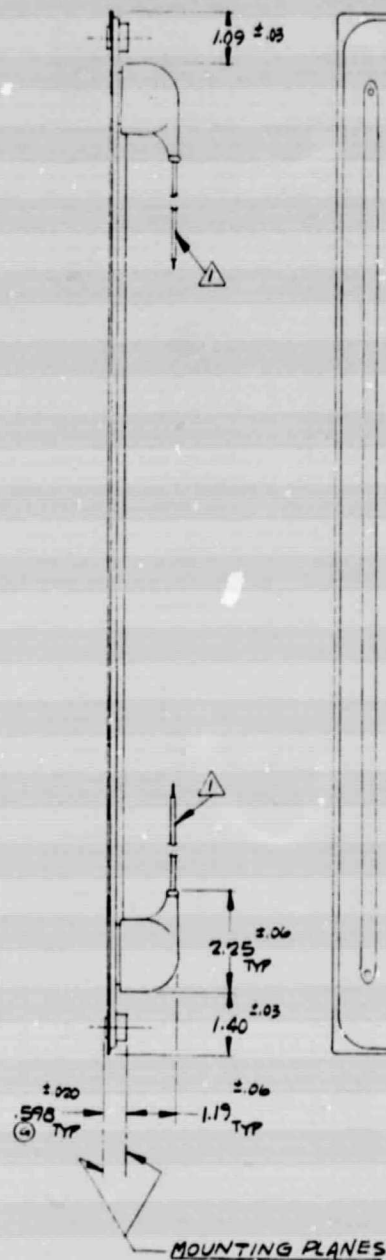
TECHNICAL DISCUSSION

A. Solar Cell Module Design

Sensor Technology's solar cell module was designed to meet the technical requirements specified in JPL Document 5-342-1 Revision B. The specification control drawing is shown in Figure 1. The design is based on an anodized aluminum stamping with ribs and flange to give it the necessary rigidity. The substrate pan is made of 5052-H32 aluminum alloy. It is stamped in a two hundred ton hydraulic press. A thin aluminum sheet is cemented to the 11.375 inch by 22.90 inch substrate. This sheet covers the ribs and creates a flat uniform surface. On top of the aluminum sheet is a PVC fiberglass mesh screen. Forty four solar cells are series connected on top of the screen. Redundant cell interconnections are made by tin plated copper strips. The solar cells are connected to redundant terminals. Surrounding the solar cells is RTV-615 silicone encapsulant. It insulates the cells from the aluminum substrate and protects the cells from the environment.



2.80 $\pm .032$ DIA
MTG HOLE
4 PLCS

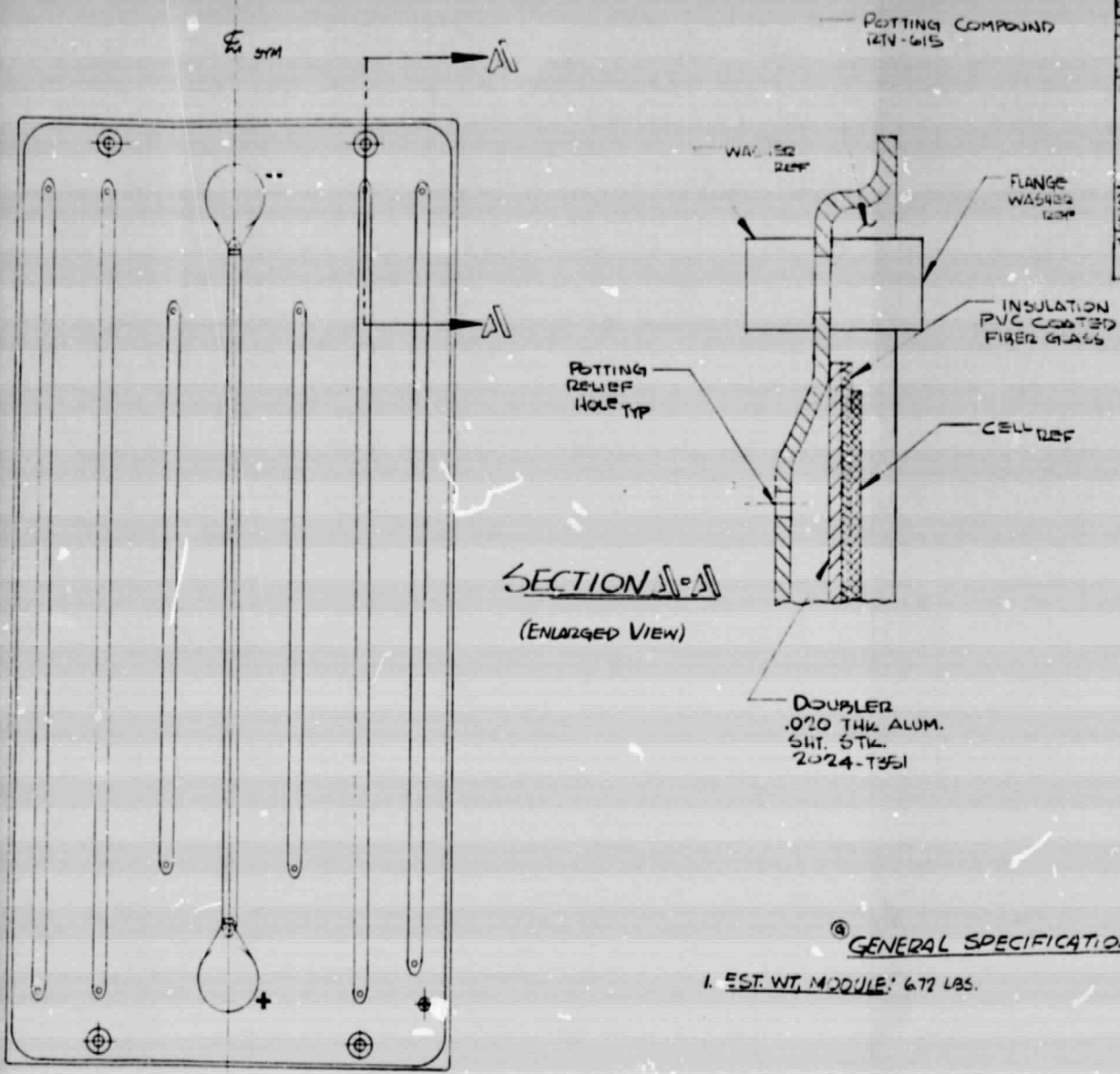


FOLDOUT FR
FOLDOUT FRAME

⚠ EXTERNAL LEAD WIRE PROVIDED BY CUSTOMER SHOWN FOR REF ONLY.

NOTES: 1. UNLESS OTHERWISE SPECIFIED

DATE	LTR	REVISION	DR	CHK	APP
7/24/74	A	DESIGN & CONSTRUCTION			
8/24/74	B	REVISED & REDESIGNED			
9/11/74	C	REVISED & REDESIGNED			
10/24/74	D	REVISED & REDESIGNED			
11/24/74	E	REVISED & REDESIGNED			
12/24/74	F	REVISED & REDESIGNED			
1/24/75	G	REVISED & REDESIGNED			
2/24/75	H	REVISED & REDESIGNED			
3/24/75	I	REVISED & REDESIGNED			
4/24/75	J	REVISED & REDESIGNED			
5/24/75	K	REVISED & REDESIGNED			



④ GENERAL SPECIFICATIONS

1. EST. WT. MODULE: 6.77 LBS.

PLANES

KOLDOUT FF
KOLDOUT FRAME

ITEM	PART NO	DESCRIPTION	REQ
TOLERANCES (UNLESS OTHERWISE SPECIFIED)		DR	1/4"
DECIMALS	XX ± .010	CHK	
FRACTIONS	XX ± .005	APP	
HOLE	± .003	USED ON	
BREAK ALL SHARP EDGES		DATE	10-10-1452
FINISH		TITLE	
MATERIAL		SPECIFICATION CONTROL CWS-97W S022 CELL MODULE	
SCALE	SIZE	DATE	SHEET
1/2"	D	20-10-1452	1 of 1

B. Electrical and Power Performance

1. Solar Cell Electrical Performance

A typical solar cell from this large scale production task is shown in Figure 2. The solar cell has a 2.15" (55mm) diameter. It is an n on p type solar cell, Czochralski grown (100) orientation.

The electrical performance of a typical solar cell is shown in Figure 3. The solar cell was tested under tungsten light at 28°C and at 100 mW.cm². At peak power a typical current voltage characteristic is 570 ma and .445 volts for a bare cell with no encapsulation. The short circuit current is 620 ma and the open circuit voltage is .55 volts. The fill factor is .744. The photovoltaic energy conversion efficiency is 10.8%.

The solar cells produced under this JPL contract were designed for large scale commercial production. They are designed for low cost, high volume production, and high efficiency.

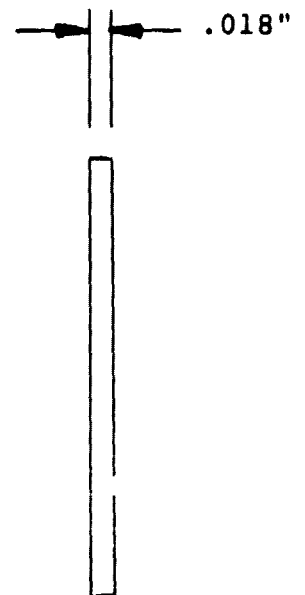
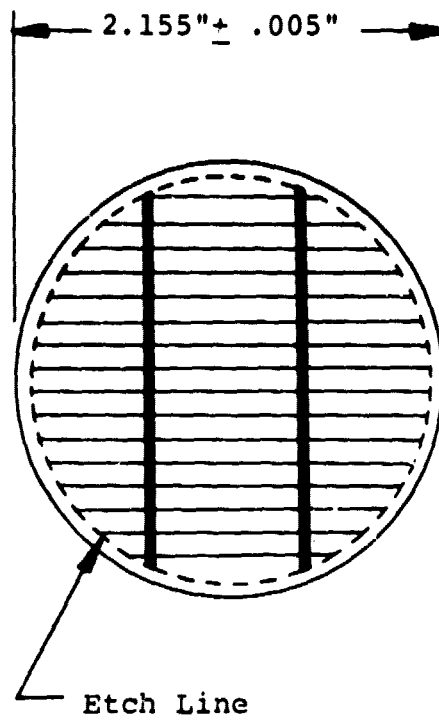


Figure 2. Sensor Technology's commercial process solar cell.

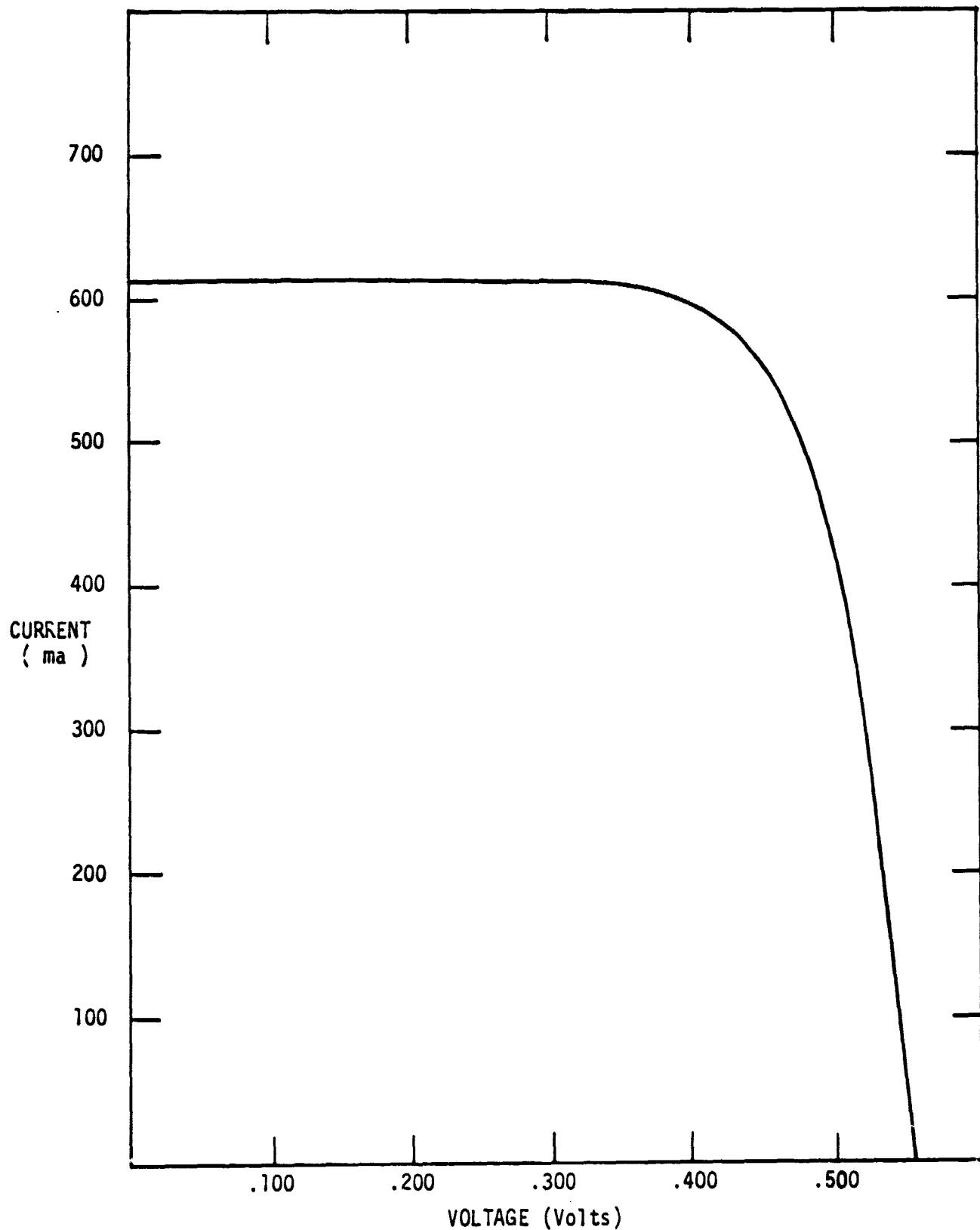


Figure 3 Electrical performance curve of Sensor Technology's commercial process Solar cell at 28° C and 100 mW/cm².

2. Module Electrical Performance

The electrical performance curve of a forty four cell series connected module is shown in Figure 4. The power shown on the curve at 16.5 volts ^{*}, 60°C and under a Xenon pulsed solar simulator at 100 mW/cm² is 9.7 watts.

The I-V curve is plotted at room temperature and the power is read from a one plot nomograph. The nomograph converts the power at room temperature, which is 24°C, 28°C, or 32°C plus or minus 2°C, to the power at 60°C measured at 16.5 volts. The curve is plotted automatically using Sensor Technology's pulsed Xenon simulator. The complete test is performed and data recorded within 20 seconds.

The average module power produced was 9.7 watts at 16.5 volts, 60°C, and at 100 mW/cm². A total of 40 kilowatts were produced.

3. Solar Cell Module Array Power Performance

Sensor Technology's solar cell module is designed to fit into a standard 4' x 4' array mounting structure. Eight series connected modules in a 4' x 4' array will produce 77.6 watts at a voltage of 132 volts, at 60°C and at 100 mW/cm² solar insolation.

* The original specification which required the module power be determined at 15.8 volts, 60°C and at 100 mW/cm² was changed by JPL to be 16.5 volts, 60°C and at 100mW/cm². The solar cell module design was changed from 42 series connected cells to 44 series connected cells to allow for greater packing density and more module power output.

SENSOR TECHNOLOGY, INC.

21012 Lassen St. Chatsworth, CA 91311

I - V Characteristic Curve

Module Serial No. 4137

Date 9/29/77

Tested by FS

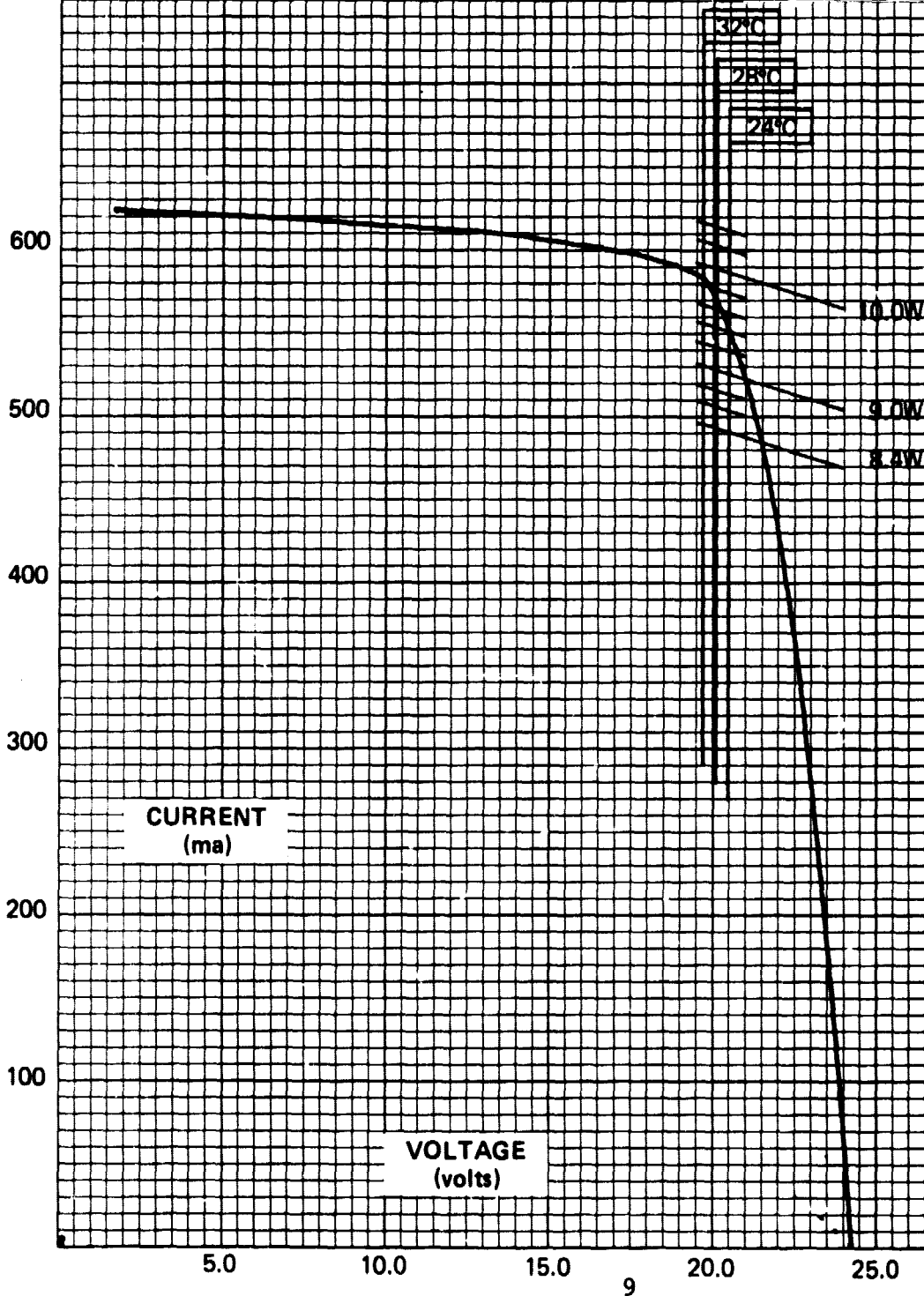
Temp. ☐ 24°C ☒ 28°C ☐ 32°C

Simulator: ☒ Xenon

Po (60°C, 16.5V) = 9.7 W

Isolation Test: ☒ Pass ☐ Reject

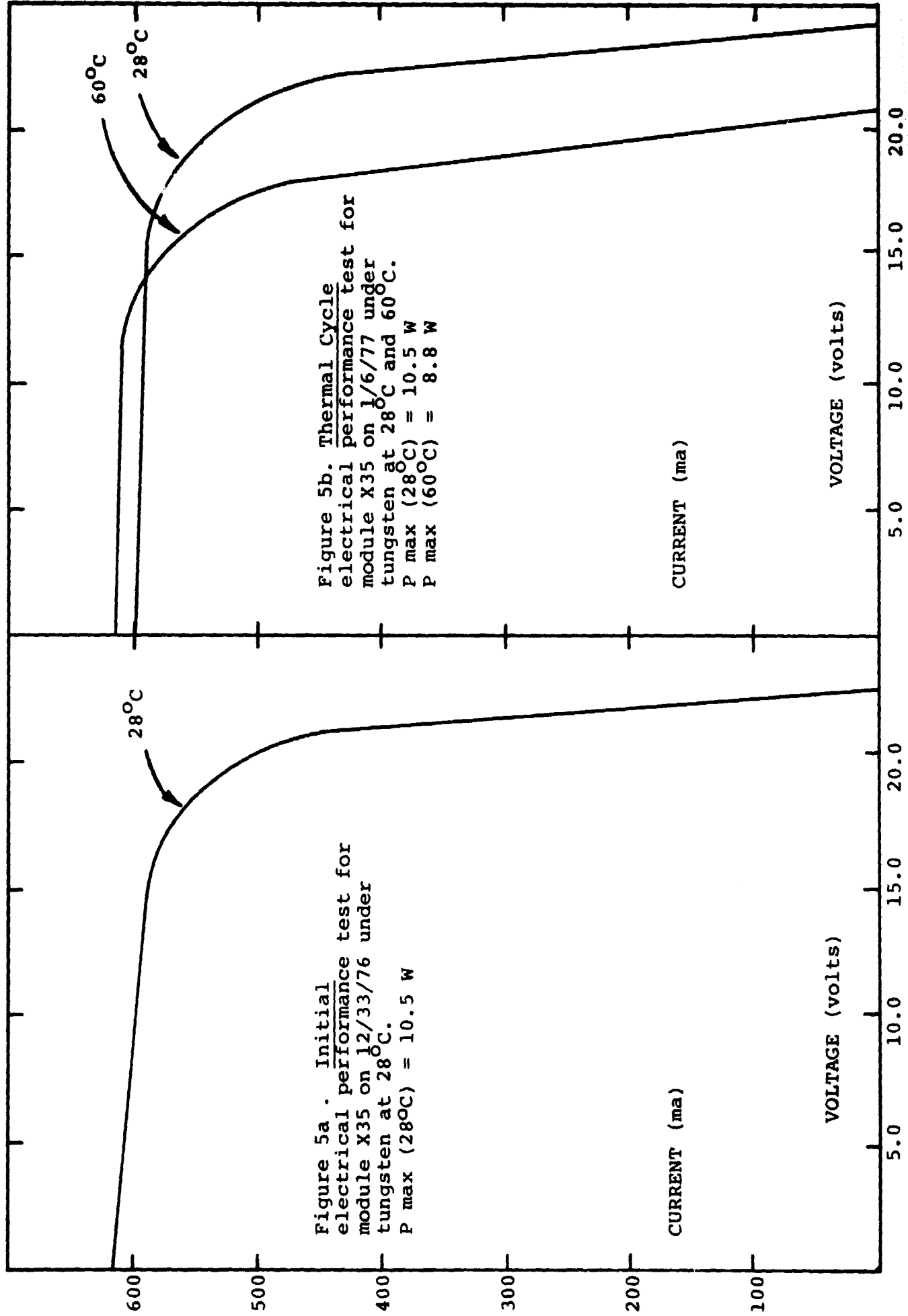
Module Repaired ☐ _____

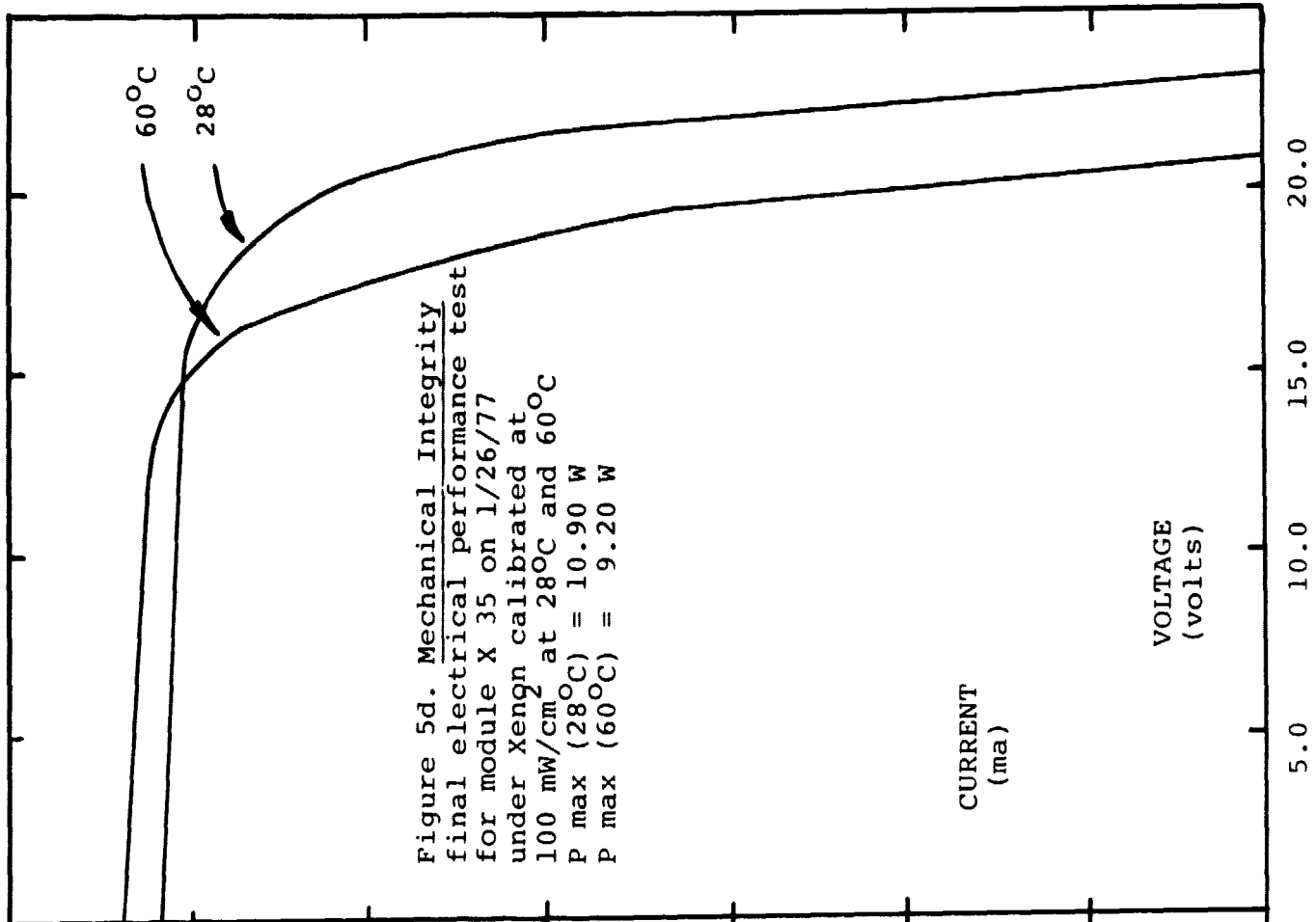
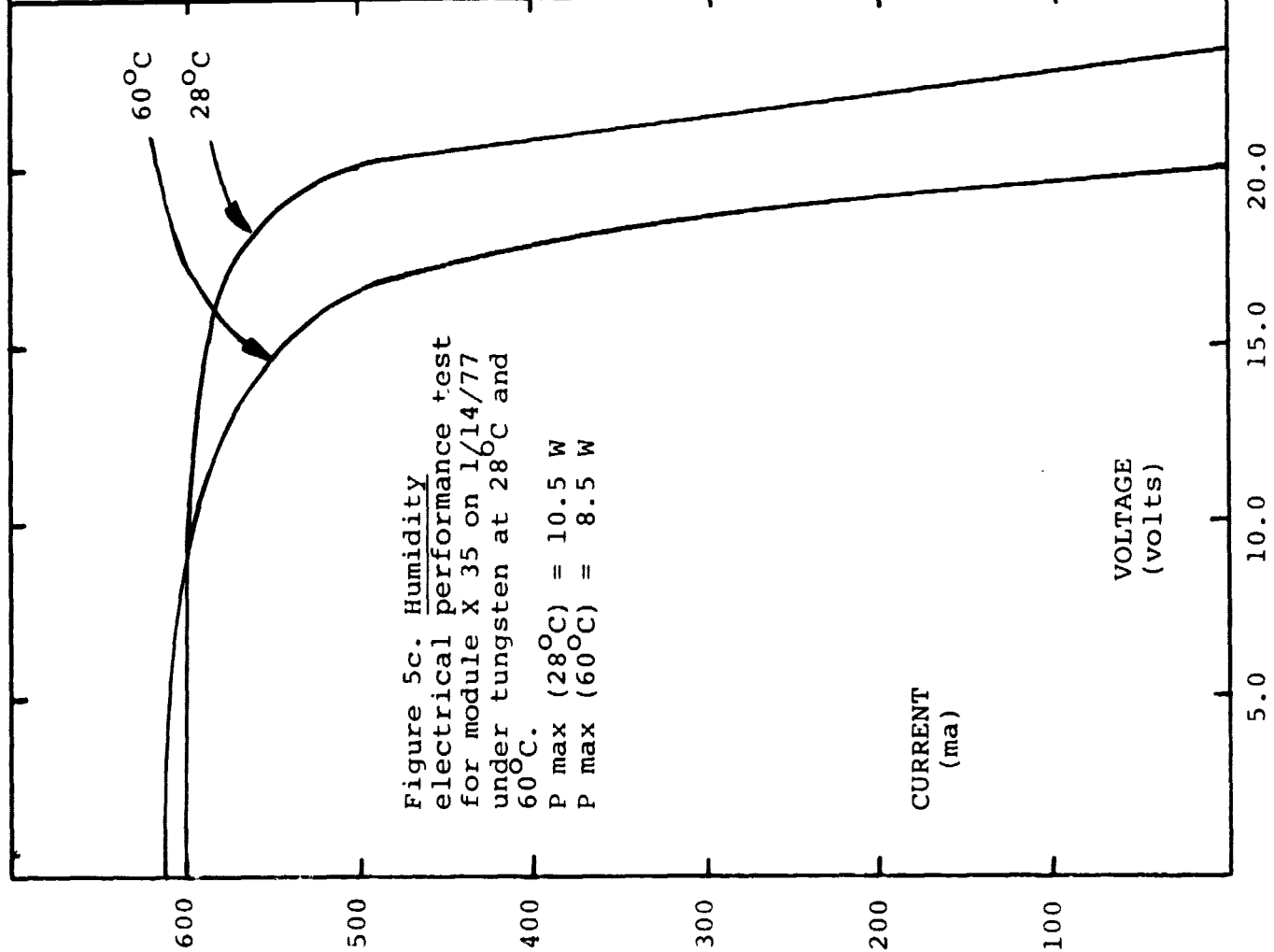


C. Module Preproduction Environmental Test Results

Forty four preproduction solar cell modules were delivered to the Jet Propulsion Laboratory for environmental tests. Ten of the forty four preproduction modules were environmentally tested per JPL document 5-342-1 revision A at Sensor Technology. The ten module serial numbers were X13, X24, X25, X28, X29, X30, X31, X32, X34 and X35. The modules successfully passed all environmental tests including thermal cycle, humidity, and mechanical integrity. Prior to and after each environmental test the modules received visual inspection, voltage (insulation) withstanding test at 1600 VDC, and electrical performance test (I-V curve) at 28°C and at 60°C.

The results of the environmental tests for preproduction module X 35 are shown in Figure 5a, 5b, 5c, and 5d. The electrical performance curves shown in the first three figures were performed under a tungsten light source. This light source was used to test preproduction modules only; a Xenon pulsed solar simulator was used to final test the preproduction modules and test all production modules. While the tungsten light source was not sufficiently uniform to obtain an accurate module power output, the electrical performance tests showed that pre-production modules remained in good condition after





each environmental test.

The final electrical performance test, shown in Figure 5d, was performed under Sensor Technology's Xenon pulsed solar simulator. The light source was calibrated to the one at JPL through the use of Sensor Technology's standard solar cell module X18. The short circuit current from our test was made to coincide with the short circuit current measured at JPL. This was manually done by adjusting the light source to module distance until the same short circuit current was achieved. The NASA/Lewis standard cell Y-46 was used to maintain this standard illumination throughout the tests. The temperature was monitored by using a thermocouple attached to the back of the module. The tests were performed at 28°C and at 60°C and maintained to within $\pm 0.5^\circ\text{C}$.

The average power of the ten preproduction 42 cell modules * was determined by Sensor Technology to be 9.18 watts/module measured at 15.8 volts, 60°C, and at 100 mW/cm² under a Xenon solar simulator.

* After 179 production 42 cell modules were manufactured JPL changed the specification to 44 cell modules. See Section B.2.

The average peak power of the ten preproduction 42 cell modules was determined to be 9.20 watts/module at 60°C and at 100 mw/cm². The peak power was very close to the power specification at 15.8 volts. The average peak power at 28°C was 10.90 watts/module. This indicated that about 16% of the module power is lost for a temperature rise from 28°C to 60°C.

D. Sensor Technology Modules (Table 1)

	<u>Modules</u>
Preproduction	44
42 cell modules	179
44 cell modules	3,890
Glass 44 cell modules	10
Total production	4,079
 TOTAL MODULES COMPLETED	 4,123

E. Module Production/Shipping Schedule (Table 2)

<u>Month</u>	<u>Shipped</u>
Dec. 1976	20 pre
Jan. 1977	20 pre
Feb.	50
Mar.	211 + 4 pre
April	150
May	737
June	805
July	667
Aug.	846
Sept.	430
Oct.	183
TOTAL	4,123

F. Module Production Summary

December 1976

1. Preproduction tests: thermal, mechanical, humidity, electrical (28°C, 60°C).
2. Q.A. plan modified.
3. Material procurement for 40 modules.
4. Solar cell assembly rack built.
5. Vacuum fixtures fabricated.
6. Design changes: terminal boot, terminal jumpers, and terminal block O-ring seal.

January 1977

1. Preproduction tests.
2. Preproduction test on four additional modules for special mounting frames.
3. Design review meeting results 1/31/77.
 - a) Optional test conditions defined.
 - b) Engineering drawings modified.
 - c) Third nut added to grounding terminal.
 - d) Acceptable power defined at 8.0 watts minimum at 15.8 volts, 60°C and at 100mW/cm², Xenon.
 - e) Q.C. # 1134 on electrical measurement to be written.
 - f) Inspection plan revised.
 - g) Production to start 2/7/77 after approval.

- h) Shipment once a week to NASA/Lewis.
- i) Statistical sampling on module acceptance/rejection to be made.

February 1977

1. Final environmental tests on 4 preproduction modules were made.
2. Production started 2/7/77 after JPL approval.
3. Testing to be made at optional test conditions as agreed between Sensor Technology and JPL.
4. Minimum power criteria defined.
5. Revised engineering drawings accepted by JPL.
6. Q.C. # 1134 approved by JPL.
7. Xenon simulator uniformity adjusted to $\pm 3\%$.
8. Q.C. Document # 1033 changed to revision B on 2/9/77 required by JPL. Figures 1, 13, 14 and 15 corrected and approved by JPL.
9. Production start up.
 - a) Ordered material.
 - b) Learning curve started for personnel & Q.C.
 - c) Drilling out 4 spacer holes to JPL specification.
 - d) Light uniformity adjusted and recorded.

- e) I-V curves recorded automatically on production graph paper with Sensor Technology's pulsed Xenon simulator.
- f) Sensor Technology's new high voltage test box used for isolation test.

March 1977

1. Preproduction lot completed.
2. Ten modules with glass covers made.
3. 179 modules with 42 cells made.
4. Modules with 44 cells were started to complete the contract requirements.
5. No change in optional test conditions made.
6. Modules shipped to MIT/Lincoln, NASA/Lewis, JPL.
7. KW samples shipped to JPL.
8. Reference Y-46 mounted to the test fixture to control uniformity to 100 mW/cm^2 .
9. Power determined at 15.8 volts, 60°C , 100 mW/cm^2 under a pulsed Xenon solar simulator.

April 1977

1. Production stopped - soldered terminals appeared to have small fractures in the solder joints.
2. Terminal fixture made to solve problem.
3. Production started and stopped - Q.C. rejection due to terminal solder problem.

4. JPL agreed to accept terminal problem.
5. Third production stoppage - aluminum pans had small forming cracks observed.
6. JPL OK's production to start again for they felt that forming cracks were only a minor problem.

May 1977

1. Aluminum forming cracks eliminated.
2. Stamping die modified and aluminum metallic grain turned ninety degrees.
3. Production accelerated to 200 modules per week to meet MIT/Lincoln Laboratory schedule.

June 1977

1. Terminals wrapped 360° after soldering which eliminated terminal problem.
2. No aluminum forming cracks observed.
3. Experimental work to fill ribs and/or cover ribs with aluminum sheet was done.
Four modules delivered to JPL.
4. Production rate continued at 200 modules per week to meet MIT schedule.

July 1977

1. Three modules with tempered glass covers were fabricated and sent to JPL.
2. Three modules each with an aluminum sheet glued to the substrate pan were fabricated and sent to JPL.
3. Production rate held at 200 modules per week.

August 1977

1. Ten modules with tempered glass covers were produced.
2. Test requirements modified by JPL to be 9.7 watts at 16.5 volts, 60°C and at 100 mw/cm².
3. Production rate continued at 200 modules per week.

September 1977

1. Aluminum substrates with aluminum sheets were made starting with serial numbers 3675. Total number made was 404.
2. Stamping die was changed to allow for holes to be punched into the ribs of the pan.
3. Insufficient supply of terminal boots delayed shipment of modules to JPL.
4. Two hundred modules shipped to JPL without boots.
5. New order of mounting bosses or spacers have tolerance problems which led to extensive rework.
6. Production was completed at 4123 modules.

October 1977

1. All modules shipped.
2. Four hundred boots to be delivered to JPL.
3. Final report to be submitted.

G. Module Delivery (Table 3)

The total number of modules delivered were 4123.
They were delivered to the following places.

JPL	2032
MIT/Lincoln Lab	1712
NASA/Lewis Research Center	379
TOTAL MODULES DELIVERED	4123

COST ANALYSIS

A cost analysis was made upon completion of contract requirements. The percentage of direct costs per module for materials and labor are shown in Table 4.

The materials include silicon wafers, cell processing materials and module fabrication materials. There are forty four silicon wafers per module; they are the largest single cost item constituting 41.7% of the module direct cost. Silicon process costs make up 14.9% of the module direct cost. The module fabrication materials consist primarily of the substrate assembly and encapsulants. The RTV-615 encapsulant is the second most costly material in the module. The module fabrication materials make up 19.6% of the module direct cost. The module direct material costs make up 76.2% of the total module direct cost.

The labor includes cell processing, module fabrication, engineering, and quality assurance. The module direct labor costs makeup 23.8% of the total module direct cost.

This large scale production contract, therefore, produces a solar cell module for a direct cost consisting of 76.2% for materials and 23.8% for labor, not including general and administrative costs or fee.

Table 4. Percentage of direct costs per module
for materials and labor

Silicon wafers (44)	41.7%
Cell processing materials	14.9%
Module fabrication materials	19.6%
Total direct material costs	76.2%
Total direct labor costs	23.8%
Total direct costs *	100.0%

* General and administrative costs and fee
are not included.

COST REDUCTION RECOMMENDATIONS

Experience gained from this Large Scale Production Task and others ^{3,4,5,6,} has shown that the major recommendation for cost reduction in the production of solar cell modules is volume orders in the range of hundreds of kilowatts per year per company as a minimum starting point and many megawatts ⁵ preferred.

There are four basic areas that this program can specifically recommend for cost reduction. They are: materials, labor, power output per unit area, and lifetime.

The material area include silicon wafers, cell processing materials, and module fabrication materials. Table 4 shows that silicon wafers accounted for 41.7% of the direct costs for a solar cell module. This cost is largely beyond our control. Even though competitive bidding, wider range of resistivity and volume orders on the order of 300,000 wafers was obtained the silicon wafer costs remained at more than half the material cost for the solar cell module. It is recommended that large volume markets be created and cost incentives be generated for the silicon material industry to bring the cost of silicon wafers down.

Cell processing materials accounted for 14.9% of the direct costs for constructing a module. The costs for chemicals and materials can be reduced through large volume procurements. Process equipment and techniques that utilize less chemicals and materials and lower cost chemicals and materials should be investigated for implementation.

Module fabrication materials accounted for 19.6% of the total direct module material costs. More than half of these material costs were for RTV-615 silicone encapsulant. Cheaper, better quality, and more durable module fabrication materials need to be developed. Sensor Technology has been able to reduce costs in this area. The next JPL procurement will utilize an aluminum extrusion substrate which replaces the aluminum pan. This extrusion which will be used in the JPL Block III buy costs about the same as the aluminum pan but utilizes less hardware. For example, it will not have four sets of mounting studs, no aluminum sheet, nor the labor and equipment for assembly. The aluminum extrusion is better quality and much more durable than the aluminum pan. Our experience using an aluminum extrusion in JPL's Block I buy has proven in the field and under accelerated testing that this design concept is excellent. The mechanical integrity of this design is outstanding. Thermal expansion and contraction of RTV-615, which was shown to be a cause for cracked solar cells, a problem, is held to a minimum with this design. The extrusion has a fin design which

will minimize temperature variation and cool the solar cells and thus, increase the solar cell module electrical power output.

Direct labor accounts for a total of 23.8% of the module costs. Automation is the key for bringing these costs down. Research and development in this area is being done,⁶ but more innovative ideas and concepts need to be pursued; funding and capital for automation equipment should be available.

More power output per unit area is necessary to get the costs per watt down. Therefore, an increase in solar cell photovoltaic conversion efficiency and an increase in solar cell nesting (or packing) efficiency is required. Sensor Technology^{5,6} is actively pursuing this area in other contracts. For example, efficient hexagonal solar cells cut by laser⁵ increase the solar cell nesting efficiency by more than 25%. This practical technique significantly increases the power output per unit area and it is adaptable to automation⁶.

Long life which leads to a high energy pay back ratio is required in order to reduce costs. Sensor Technology has taken a major step toward achieving a long module lifetime. The aluminum extrusion substrate which will be used in the next JPL Block III procurement will protect the solar cells from the environment.

Cracked solar cells, a problem, will be minimized with this design (see above). The extrusion design concept will reduce encapsulant delamination. The overall solar cell module is designed to meet a higher quality assurance standard set by the Jet Propulsion Laboratory.⁷ However, significant work must continue in this area and innovative ideas⁸ should be funded.

CONCLUSIONS

Sensor Technology is one of the principle manufacturers in the Large Scale Production Task. Forty kilowatts of solar cell modules was produced in this procurement. This is equivalent to 4123 solar cell modules. The average power per module was 9.7 watts at 16.5 volts, 60°C and at 100 mw/cm². The peak production rate was 200 modules per week or 1.9 KW per week. This rate was sustained for over four and one half months. Thus, Sensor Technology could have continued producing modules at a rate of 100 KW per year for JPL/DOE procurements, in addition to commercial sales orders. Since the completion of this procurement and the writing of this report Sensor Technology has more than doubled its solar cell module manufacturing facilities. We have the present capability of producing 300 KW per year for JPL/DOE procurement in addition to commercial sales orders. We are in the process of expansion of our facilities to meet growing JPL/DOE procurements to 500 KW and later on this year to 1 Megawatt.

LIST OF APPLICABLE ENGINEERING DRAWINGS

<u>Part Number</u>	<u>Rev.</u>	<u>Description</u>
D 20-10-1452	K	SCD - 9.7 watt Solar Cell Module
D 10-10-1652	E	Panel Assembly
D 10-10-1653	G	9.7 watt Solar Cell Assembly
D 10-10-1655	C	Solar Cell Array
C 10-10-1667	G	Panel, Solar Cell

LIST OF REFERENCES

1. National Photovoltaic Plan; Morton B. Prince, Chief, Photovoltaic Branch, ECDA; Proceedings of the Second ERDA Semi-Annual Solar Photovoltaic Program Review Meeting, January 20-22, 1976 at Lake Buena Vista, Florida; Conf. 76031.
2. Low-Cost Silicon Solar Array Project; Robert G. Forney; Project Manager; Jet Propulsion Laboratory; California Institute of Technology; Proceedings of the Second ERDA Semi-Annual Solar Photovoltaic Program Review Meeting; January 20-22, 1976 at Lake Buena Vista, Florida, Conf. 76031.
3. Fabrication, Test & Delivery of 8 KW of Solar Power Modules, Final Report; JPL Contract 954387; LSSA Project; Large Scale Production Task; October 15, 1976; Sensor Technology, Inc.
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